Design Practice for Known Beam-Loss Locations (BLLs)

Introduction

When a high-energy charged particle, such as a proton, leaves the vacuum confine of an accelerator, it encounters various materials along its flight path. These materials, which are used in the magnetic transport components, vacuum pipes, cooling system, tunnel environment and radiation protection shielding, are various metals such as aluminum, copper and steel, as well as air, water, concrete and soil.

Particles such as neutrons, other protons and other nuclear fragments may be produced along the path of the high-energy particle. That happens when a nucleus is struck by a high-energy particle, it may be broken into smaller pieces. At high-energy accelerator energies (e.g., AGS and RHIC), tens to hundreds of nuclei may be broken-up by these "spallation reactions" when dissipating the energy carried by a single high-energy particle. The kinds and quantities of fragments produced depend upon various factors such as the type and energy of the incident particles, the composition of the material struck, the species and energy spectrum of the fragments arising out of the collision and the production probability of the fragment concerned.

A commonly produced fragment in most spallation reactions is a nucleus with two neutrons and a proton, which is the radionuclide known as tritium. The amount of tritium radioactivity present at any given time will depend upon tritium's half-life and the time since production of the tritium has ceased, the flux of high-energy particles and the actions taken to reduce the tritium concentration in the irradiated material (e.g., drain and refill of activated water systems). There are many other spallation fragments that are also radioactive; however, most are very short lived, minutes to days. A few longer-lived radionuclides are produced but most are immobile, with the exception of tritium and

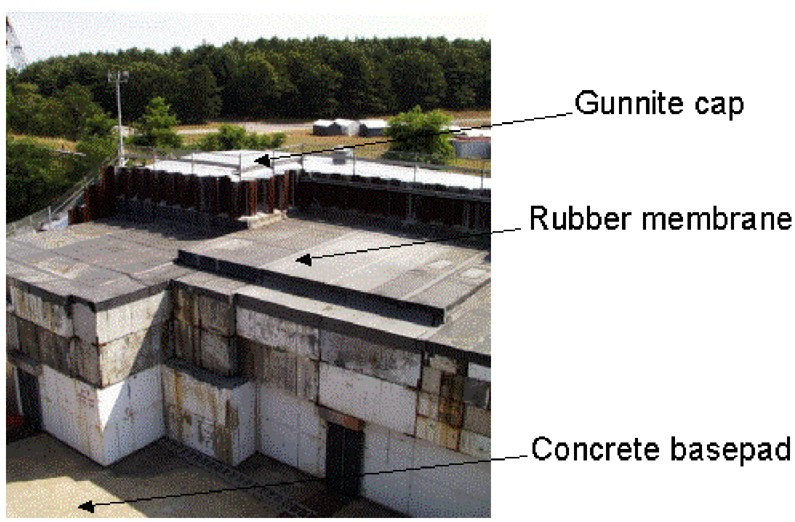
^{22}Na. When one considers the problem of activation of soil and subsequent groundwater contamination, not only half-life but also mobility and transit time of a given radionuclide from its production point to the water table are key parameters.

The term "activation" refers to the process of creating radionuclides in materials such as concrete or soil-shields via the spallation reaction. Soil shields used near beam stops and targets are termed "activated soil" because they contain ^{22}Na and tritium.

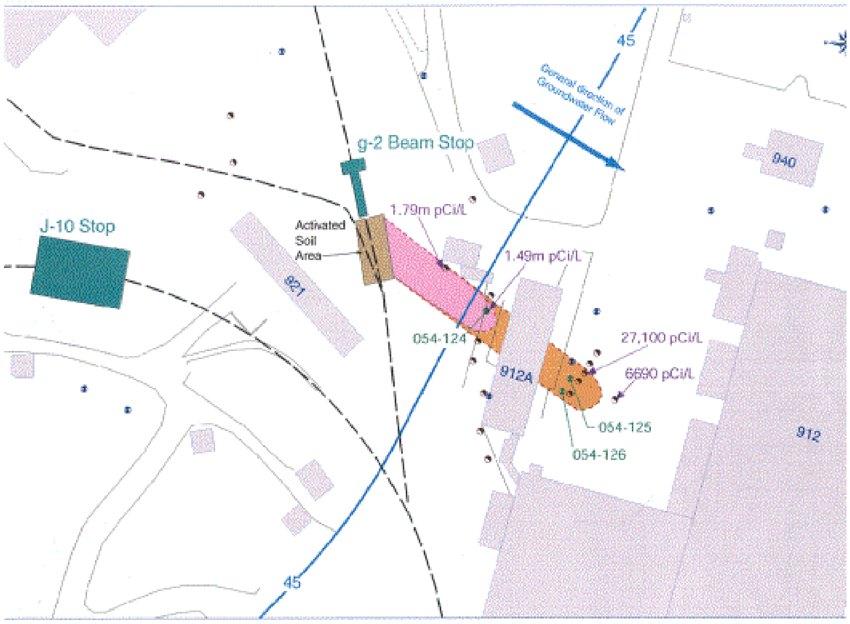
If rainwater percolates through activated soil in the vadose zone, it can leach tritium and ^{22}Na into the groundwater. By preventing the leaching of tritium and ^{22}Na via rainwater in soil, the introduction of radionuclides into the water table is prevented. Reducing the amount of soil activation by using other types of material for shielding or by using engineering controls to reduce beam loss are additional pollution-prevention opportunities. Soil is an ideal radiation shield for human protection. It is dense, conforms to desired shapes, does not deteriorate and is inexpensive. The addition of an impermeable, second shield above the activated soil, the rain barrier, prevents the leaching.

The following illustrates the leachate problem with and without an impermeable water barrier.

Caps Over Known Beam Loss Location



Plume From Uncapped Activated Soil



The objectives of the following design practices are to operate within regulatory requirements, and to integrate pollution prevention and waste minimization into the decision process that results in minimal beam loss in soil. Mitigation of leachate from activated soil is the minimum requirement, and it is to be carried out by capping activated soil.

An evaluation of pollution prevention opportunities leads to the following design practices that are further elaborated upon:

- Determine beforehand via calculations the amount of residual ^{22}Na and ^{3}H created in the soil,
- Determine beforehand via calculations the concentration of radionuclides in any potential leachate from an uncapped region of activated soil,
- Minimize the amount of residual radioactivity in soil using iron and concrete shielding,
- Eliminate potential radioactive effluent from known beam loss locations by capping with effective, maintained water impermeable barriers, and
- Monitor the effectiveness of the design practices.

<u>Standardized Calculation of Soil Activation</u>

Only the radionuclides tritium and ^{22}Na need be considered because of their longer half-lives and mobility.

As part of the evaluation, annual activity concentrations in soil are to be estimated. This requires an estimate of beam loss in a year, the density of hadron interactions as a function of position in soil near the beam loss point(s), and the production probability of tritium and ^{22}Na per interaction.

The density of hadron interactions is normally estimated by Monte Carlo codes. The nuclide production may be estimated by Monte Carlo code. For example, MCNPX is capable of directly estimating tritium production. An alternative to direct nuclide production evaluation is to use measured values "per CASIM star." These numbers, which correspond to the production probability in soil from a neutron spectrum rapidly falling from 47 MeV, are 0.075 tritium nuclides per star (per interaction) and 0.02 ^{22}Na per interaction. The error on this measurement is at least a factor of 1.5.

The maximum annual activity concentration in water due to direct radionuclide production at the position of the water table shall be estimated. This should be taken to be 10 times the activity concentration in soil multiplied by the leachable fraction, which is 1.0 for tritium and 0.075 for ^{22}Na. In the most common case, the water table is a considerable distance below the position of maximum concentration in soil. The fall-off of transverse interaction density is

$$\frac{e^{-\left(\frac{d}{L}\right)}}{R_T^2}$$

where d is the thickness of shield, L is the interaction length of the shielding material, and R_T is the transverse radial distance from the beam. The transverse interaction length L can be estimated from Monte Carlo, but should not be taken to be lower than the Tesch value, which is L = 60 cm for soil-shield density of 1.8 g/cc, assuming the beam energy is 2 GeV or above.

Standardized Calculation of Radioactivity Concentration in Leachate

Assuming the maximum annual activity concentration in soil is above the water table, the maximum activity in water at the water table due to leaching by rain should be estimated using the model of Lessard[1]. In the example model (see Tables 1 and 2), $3.7\text{x}10^8$ atoms tritium/cc in one year (soil) results in the drinking water limit of 20,000 pCi/L (water) and $2.1\text{x}10^7$ atoms ^{22}Na/cc in one year (soil) results in the drinking water limit of 400 pCi/L (water). In these expressions, the soil radionuclide-concentrations are evaluated at the position of maximum soil radionuclide concentration.

[1] E. J. Bleser, "Shielding for the AGS J10 Scraper, AGS/AD/Tech. Note No. 444, Accelerator Division, Alternating Gradient Synchrotron Department, Brookhaven National Laboratory, Upton, New York 11973, September 13, 1996.

TABLE 1

Quantity	Value	Units
^{22}Na Atoms per unit volume of soil in one year	2.13E+07	atoms/cc_{soil}
Available atoms per unit volume of soil since 7.5% of ^{22}Na is leachable	1.60E+06	atoms/cc_{soil}
Fraction of soil that is water	0.1	
Concentration factor since 1 unit volume of water can leach nuclides from 10 unit volumes of soil	10	
Dilution factor:		
a. Radioactive atoms are essentially contained in a 1/e thickness of irradiated soil	60	cm
b. fraction of soil that is water	0.1	
c. height of water column in 1/e thickness of soil	6	cm
d. annual rainfall that percolates down to groundwater	55	cm
e. dilution per year = 55/6	9	
Overall concentration factor of leachable atoms from soil to water	1.1	
Annual average ^{22}Na atom concentration in effluent	1.76E+06	atoms/cc_{water}
Half-life of ^{22}Na	2.60E+00	year
Annual average ^{22}Na activity concentration in effluent	4.01E+02	pCi/L

TABLE 2

Quantity	Value	Units
^{3}H Atoms per unit volume of soil in one year	3.75E+08	atoms/cc_{soil}
Available atoms per unit volume of soil since 100% of ^{3}H is leachable	3.75E+08	atoms/cc_{soil}
Fraction of soil that is water	0.1	
Concentration factor since 1 unit volume of water can leach nuclides out of 10 unit volumes of soil	10	
Dilution factor:		
a. Radioactive atoms are essentially contained in a 1/e thickness of irradiated soil	60	cm
b. fraction of soil that is water	0.1	
c. height of water column in 1/e thickness of soil	6	cm
d. annual rainfall that percolates down to groundwater	55	cm
e. dilution per year = 55/6	9	
Overall concentration factor of leachable atoms from soil to water	1.1	
^{3}H atom concentration in effluent	4.13E+08	atoms/cc_{water}
Half-life of ^{3}H	1.24E+01	year
^{3}H activity concentration in effluent	1.98E+04	pCi/L

Beam Tuning To Minimize Beam Loss

The accelerator management shall design beam loss to soil such that levels that are as low as reasonably achievable with operational, economic and community factors taken into account. As a minimum, the accelerator management shall meet the following requirements:

- Responsibility for determining acceleration, extraction and transport loss limits for setting threshold values to activate alarms shall be formally assigned by the management of the accelerator.

- Changing acceleration, extraction and transport loss limits as operations evolve shall be done via a formal approval mechanism.
- Accelerator management shall assign responsibility for determining appropriate instrumentation for measurement of the losses, and for ensuring measurements are reviewed at appropriate intervals in order to validate loss assumptions.
- Accelerator management shall ensure that alarm threshold values used by operations personnel are incorporated into the appropriate computerized controls programs.

Management shall ensure that operations procedures contain loss limits. Response by operators to alarms shall be clearly written in procedures. Loss problems shall be corrected within minutes, otherwise operators shall reduce the beam intensity to the affected area. Accelerator operations staff shall determine whether there will be a negative impact on the environment, safety or health of workers, a negative impact on the physics program, or a negative impact on accelerator equipment if prolonged high-loss operation is permitted. Authorization for prolonged high-loss operation, with an alarm present, shall come from the highest-level manager of the accelerator and be documented.

Management shall ensure that the responsibility for maintaining loss-monitor systems is assigned. Beam current transformers and loss monitors used to determine operating efficiencies and losses shall undergo verification by the operations staff in the control room at start-up of a running period.

Residual radiation surveys on new elements or new beam lines shall be made after the first operational running period in order to confirm loss assumptions.

Standard for Prevention of Rainwater Infiltration

The accelerator management shall prevent leachate from activated soil due to rainwater or stormwater such that levels are as low as reasonably achievable with operational, economic and community factors taken into account. As a minimum, the accelerator management shall meet the following requirements:

- Annual activity concentration in leachate should be prevented if it is calculated to be measurable in rainwater leachate.
- A cap should be applied to activated soil to eliminate exposure to rainwater.
- If the annual activity concentration in leachate is calculated to exceed 0.05 (5%) of the drinking water standard, then a cap shall be used unless the BNL management is convinced otherwise. That is, impermeable caps shall be required for soil activation areas where the predicted annual activity concentration in leachate, leachate that may be created by infiltration of rainwater or stormwater runoff through activated soils exceeds 1,000 pCi/L for tritium or 20 pCi/L for Na^{22}.

The water of interest for the activity-concentration calculation is rainwater/stormwater leachate. It is not the concentration in groundwater at the "point of assessment." It is noted that leachate concentrations at 0.05 (5%) of the drinking water standard are not anticipated to be measurable at the "point of assessment." See Verification by Monitoring for further discussion of "point of assessment."

A hydraulic barrier layer or cap is to be designed to prevent or minimize rainwater infiltration into the activated soil areas. The cap shall be designed to incorporate the following criteria as a minimum:

- The peak rainwater infiltration rate is less than or equal to the infiltration rate in 18 inches of low permeability soil (hydraulic conductivity less that $1x10^{-5}$ cm/sec) with one inch of ponded water above the cap. This equates to an allowable peak infiltration rate of approximately 1 cm/day. This is approximately 0.3% of the infiltration rate for natural soils at BNL.

- The long term average infiltration rate, as estimated with the Hydrologic Evaluation Landfill Performance (HELP) Model, Version 3.07 or newer,[2] is less than 0.12 cm/year (0.047 inches/year). This is approximately 0.2% of the natural groundwater recharge rate at BNL.

Direct Activation of Groundwater

The accelerator management shall prevent direct activation of groundwater to levels that are as low as reasonably achievable with operational, economic and community factors taken into account. As a minimum, the accelerator management shall meet the following requirements:

- The highest level of the water table shall be determined based on archival information for the BLL site.
- The shield thickness or alternatively the thickness of soil in the vadose zone shall minimize direct activation of groundwater.
- For direct activation of groundwater, if the estimate of annual radioactivity concentration produced directly in the groundwater at its highest level exceeds 0.05 (5%) of the drinking water standard, then the physical configuration is not acceptable. Planned losses shall be reduced, the distance to the water table shall be increased or the shielding between the BLL and the groundwater shall be increased.

Acceptable BLL Capping Materials

- Concrete or Gunnite Overlay (Conventional)

[2] USEPA, "The Hydrologic Evaluation of Landfill Performance (HELP) Model," Version 3.07. EPA Office of Research & Development, 1995.

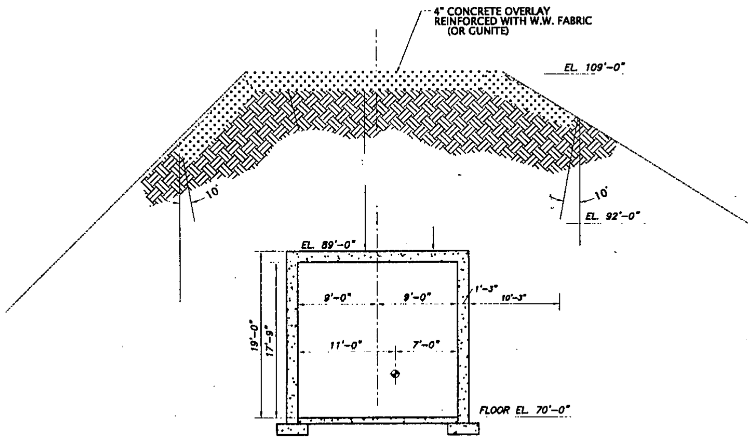
    - The cap shall be placed directly over the area to be protected, reinforced with welded wire fabric and meet the American Concrete Institute code. The cap shall be sealed to existing structures using flexible sealants or grouts.
- Geomembrane Covers (Conventional)
    - Standard landfill geomembranes and construction techniques may be used. The geomembrane cap shall meet the general requirements of 6NYCRR, Part 360, 2.13, R.
- Low Permeability Soil Covers (Conventional)
    - A minimum 18-inch thickness of low-permeability, properly pre-planned barrier soil, meeting the general requirements of 6NYCRR, Part 360, 2.13, J and Q, may be used.
- Metal or EPDM Roofing (Alternative)
    - Standard roofing technique may be used if they meet the building code and the manufacturer's recommended instructions. The roofing shall be sealed to existing structures using flashing and sealants.

Innovative or alternative capping systems such as metal roofing, rubber membranes such as EPDM or paving may be used if it is demonstrated that the infiltration-rate design-criteria will not be exceeded (see Standard for Prevention of Rainwater Infiltration). This demonstration shall be made using the HELP model analysis[2] or moisture monitoring from beneath the capping system using lysimeters or equivalent.

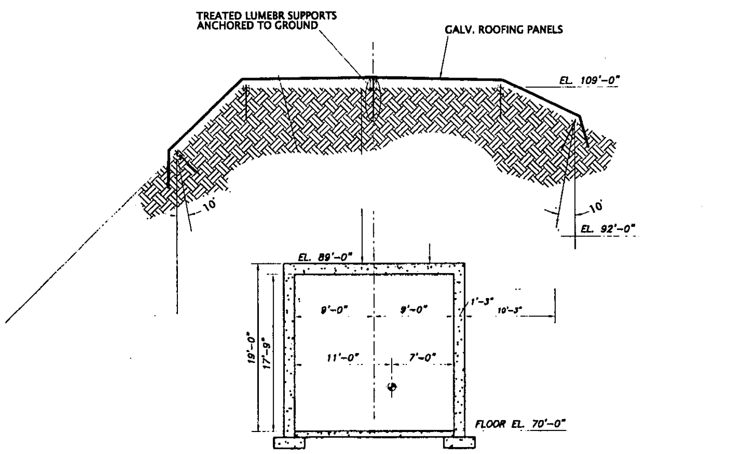
Validating the As-Built Cap

- The as-built cap structure shall be inspected and validated against design drawings.
- The as-built cap overlap shall be inspected and validated.
    - The cap shall overlap the activated soil that is to be protected by 10 degrees as shown in the following illustrations.

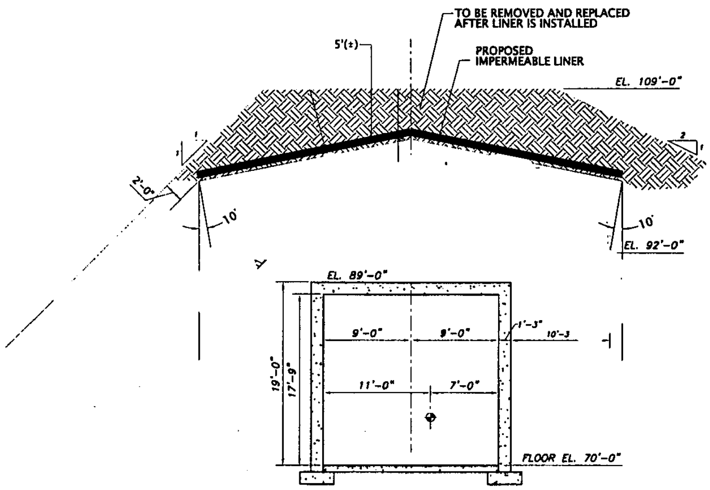
It is noted that for below-grade caps, visual inspection for overlap is possible during the construction phase. However, below-grade caps are not able to be directly inspected for tears or cracks after construction. On-the-other-hand, soil used at a BLL is constructed uniformly and tested since it is used as radiation shielding. It is not undisturbed local soil. Soil shields are homogeneous in composition. Below-grade caps are not exposed to animals or other surface sources of penetration. If installed properly, the chief concerns for below-grade caps are: 1) soil erosion that can expose the membrane and 2) trees whose roots can damage the membrane, and both concerns shall be monitored (see Preventive Maintenance Schedule and Reporting). The project engineer in charge of installing the cap shall validate the as-built structure against the design drawings, and update the drawings according to internal change procedures. See Internal and External Approvals.



CONCRETE OVERLAY OR GUNNITE METHOD Conventional



METAL ROOFING METHOD Alternative



LINER METHOD Conventional

Stormwater Management

Stormwater runoff from capped beam-loss areas shall be collected and conveyed to the BNL stormwater collection system, when practicable. If the BNL stormwater system is not convenient, then stormwater runoff shall be collected and discharged to an area outside the area of beam loss influence. The following design considerations shall be reviewed during design of loss areas:

- Stormwater run-on from adjacent areas shall be prevented.
- The design shall not allow a direct pathway from the stormwater piping or recharge system through a beam-loss location.
- Drywells, if necessary shall be located at least 100 feet outside the beam-loss areas. All drywells shall be approved by the BNL manager who has that authority.
- Rooftop drainage from adjacent structures shall be conveyed away from beam-loss areas.
- Storm, sanitary and domestic water piping shall not be located within beam-loss area.

Preventive Maintenance Schedule and Reporting

BLL caps shall be inspected at the start-up and conclusion of each running period, which is typically twice per year. In no case shall inspection of all caps be less frequent than annually. Sufficient time should be allowed before operations to allow for repairs. A written procedure shall be used to conduct inspections. A record of inspection shall be maintained in accordance with internal operating procedures. The following items shall be inspected and they shall be specifically listed in internal operating procedures:

- Check for penetrations such as cracks in concrete or Gunnite caps.
- Check sealed areas such as penetrations or fence posts or sheet piling.
- Check for holes, cracks or tears in waterproof membranes such as EPDM rubber roofing membrane.
- Check for excessive ponding of rainwater.
- For above-grade, below-grade caps and paved areas, check for trees and woody shrubs whose roots can damage the cap.
- For below-grade caps, check for soil erosion that can expose the membrane.

Preoperational Monitoring (Baseline)

Wells shall be installed and sampled before the operation of the facility to obtain DOE required pre-operational monitoring data. At a minimum, two sampling events in two separate calendar quarters should be conducted. See Establishing Environmental Monitoring Programs Subject Area.

Soil samples in the area of planned beam loss locations shall be obtained before new operations are conducted at the facility or beam line. Since beamlines are re-used for new experiments, and since accelerators evolve in order to be used for different modes of operation, the purpose shall be to provide a baseline level of soil activation. A sufficiently representative number of soil samples are recommended. Accelerator management shall decide the number and location of soil samples based on planned beam-loss locations, former beam-loss locations, soil locations not planned to be activated, and energy and type of particles accelerated.

Verification by Monitoring

BNL has a comprehensive environmental monitoring program that includes monitoring the air, drinking water, surface water, groundwater, soil, sediment, flora and fauna. Guidance for the evaluation of environmental monitoring requirements at BNL is provided in the Environmental Monitoring Subject Area. This program is designed to provide early warning of potential environmental releases, monitor potential pathways for exposure to the public and the environment, monitor the effectiveness or environmental remediation systems, measure the potential impact BNL operations may have on the environment, and provide data to demonstrate compliance with applicable laws, regulations, and permit limits. It includes planning, implementation and reporting activities associated with the collection and analysis of samples, or the direct measurement of environmental media, including liquid effluent monitoring, air emissions monitoring, and environmental surveillance.

Groundwater monitoring is a means of verifying that operational and engineered controls at BLLs are effective in protecting groundwater quality. Verification of groundwater quality is based on actual measurements at the groundwater “point of assessment.” A hydrogeologist along with other Subject Matter Experts shall determine the "point of assessment" (see Environmental Monitoring Subject Area).

When establishing a groundwater monitoring program:

- Groundwater monitoring programs shall be established in soil activation areas that are capped. A staff hydrogeologist shall evaluate the geology and hydrology of the potential soil activation area.
- The wells shall be positioned as close as reasonably achievable to known or potential soil activation.
- The number of wells required for a monitoring program shall be based upon the size of the potential soil activation area, and take into account potential variations in groundwater flow directions due to natural or synthetic effects (i.e., pumping and recharge effects).
- Typically, two downgradient wells shall be required for small activation areas.
- Upgradient wells may be required if other known or potential soil activation sources may influence measurements at the "point of assessment."
- All monitoring wells shall be installed according to BNL requirements (see Environmental Monitoring Subject Area).
- Depth of the wells and location of the screened sections shall be based upon depth to groundwater and complexity of potential contaminant migration pathways.
- Groundwater modeling may be used to assess contaminant migration pathways and rates.
- Typically for wells located close to a potential soil activation area, the well's screened section should be 20 feet in length, and installed across (i.e., straddling) the water table to accommodate fluctuations in water table position.
- A groundwater sampling and analysis plan shall be developed, and incorporated into the annual BNL Environmental Monitoring Plan as per relevant DOE Order. Factors to consider when defining the frequency of sampling (i.e., annual, semi-annual, or quarterly) should be: archival and current water quality data; the potential for a contaminant release; distance from the soil activation area to the well(s) and groundwater flow velocity; and the proximity of the soil activation area to active potable water supply wells.
- All monitoring wells shall be sampled according to BNL requirements (see Environmental Monitoring Subject Area).
- Groundwater samples shall be analyzed for tritium and Na^{22} using methods acceptable to the EPA.
- All groundwater data should be stored in, and be accessible through, the BNL Environmental Information Management System (EIMS).
- The BNL Groundwater Contingency Plan will be used to respond to monitoring results that are above established thresholds described in the plan.
- If groundwater monitoring indicates that the sources pose a continuing threat to groundwater quality (i.e., concentrations at the point of assessment exceed stated thresholds), then the need for additional protective measures shall be evaluated.

- The continued adequacy of the monitoring program should be periodically verified. Additional wells may be required if significant changes groundwater flow directions are observed.

Verification by Soil Sampling

Direct measurement of soil program shall be incorporated, where practicable, into the conduct of operations. A direct soil-sampling program shall:

- Provide a baseline, see Preoperational Monitoring (Baseline)
- Verify/benchmark soil-activity calculations.
- Establish soil-sampling access ports at beam height, where practicable, which is likely the location of maximum soil-activity concentration.
- Meet sample Volume and Container Requirements.
- Comply with relevant Radiological Control Procedures.

Incorporate Lessons Learned

There are two elements to incorporating Lessons Learned: (1) conform to the SBMS Lessons Learned Subject Area, which will track off-normal performance of these engineered controls and (2) track and trend results from inspections of cap systems and results from maintenance requirements. Nonconformance shall be reported in accord with SBMS requirements.

Accelerator management shall demonstrate that these sources of information have been incorporated into their formal conduct-of-operations procedures.

Internal and External Approvals

The following shall be approved or documented by the accelerator manager/department chair or designee according to internal formal conduct-of-operations procedures:

- As-built drawings for caps and membranes.
- Locations for loss monitors.
- Procedures for cap maintenance.
- Procedures for response to loss monitor alarms.
- Benchmark soil-activity calculations.

The following shall be approved or documented by the appropriate BNL environmental Subject Matter Expert:

- A design review according to requirements in SBMS or according to requirements in accelerator department procedures (e.g., C-A OPM 9.2.1 or C-A OPM 9.3.1).
- Monitoring well locations.
- Type and number of monitoring wells.